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# Ionospheric Calibration for Single Frequency Altimeter Measurements

## Final Report

Award #Nag-1-1491  
21 March 1994

William S. Schreiner, George H. Born, and Robert E. Markin

Colorado Center for Astrodynamics Research  
Department of Aerospace Engineering Sciences  
University of Colorado, Boulder, CO 80309-0431

(NASA-CR-195709) IONOSPHERIC  
CALIBRATION FOR SINGLE FREQUENCY  
ALTIMETER MEASUREMENTS Final Report  
(Colorado Univ.) 26 p

N94-27883

Unclassified

G3/46 0000903



## Abstract

This study is a preliminary analysis of the effectiveness (in terms of altimeter calibration accuracy) of various ionosphere models and the Global Positioning System (GPS) to calibrate single frequency altimeter height measurements for ionospheric path delay. In particular, the research focused on ingesting GPS Total Electron Content (TEC) data into the physical Parameterized Real-Time Ionospheric Specification Model (PRISM), which estimates the composition of the ionosphere using independent empirical and physical models and has the capability of adjusting to additional ionospheric measurements. Two types of GPS data were used to adjust the PRISM model: GPS receiver station data mapped from line-of-sight observations to the vertical at the point of interest, and a grid map (generated at the Jet Propulsion Laboratory) of GPS derived TEC in a sun-fixed longitude frame. The adjusted PRISM TEC values, as well as predictions by the International Reference Ionosphere (IRI-90), a climatological (monthly mean) model of the ionosphere, were compared to TOPEX dual-frequency TEC measurements (considered as truth) for a number of TOPEX sub-satellite tracks. For a 13.6 GHz altimeter, a Total Electron Content (TEC) of 1 TECU ( $10^{16}$  electrons/meter<sup>2</sup>) corresponds to approximately 0.218 centimeters of range delay. A maximum expected TEC (at solar maximum or during solar storms) of  $10^{18}$  electrons/meter<sup>2</sup> will create 22 centimeters of range delay. Compared with the TOPEX data, the PRISM predictions were generally accurate within the TECU when the sub-satellite track of interest passed within 300 to 400 km of the GPS TEC data or when the track passed through a night-time ionosphere. If neither was the case, in particular if the track passed through a local noon ionosphere, the PRISM values differed by more than 10 TECU and by as much as 40 TECU. The IRI-90 model, with no current ability to ingest GPS data, predicted TEC to a slightly higher error of 12 TECU.

The performance of PRISM is very promising for predicting TEC and will prove useful for calibrating single frequency altimeter height measurements for ionospheric path delay. When adjusted to the GPS line-of-sight data, the PRISM URSI empirical model predicted TEC over a day's period to within a global error of 8.60 TECU rms during a nighttime ionosphere and 9.74 TECU rms during the day. When adjusted to the GPS derived TEC grid, the PRISM parameterized model predicted TEC to within an error of 8.47 TECU rms for a nighttime ionosphere and 12.83 TECU rms during the day. However, the grid cannot be considered globally due to the lack of sufficient numbers of GPS stations and large latitude gaps in GPS data. It is the opinion of the authors that using the PRISM model and adjusting to the global sun-fixed TEC grid regenerated with a localized weighted interpolation offers the best possibility of meeting the 10 TECU global rms (or 2 cm at 13.6 GHz) ionosphere range correction accuracy requirement of TOPEX/Poseidon and should be the subject of further study. However, it is clear that the anticipated requirement of 3-4 TECU global rms for TOPEX/Poseidon Follow-On (corresponding to the TOPEX/Poseidon performance) can not be met with any realizable combination of existing models and data assimilation schemes.



# Introduction

## Background

Satellite altimetry has become a very powerful tool for the study of ocean circulation and variability, and it may provide the best chance of understanding the important issues related to climate and global change. Sea surface height measurements are computed by combining the radar altimeter measurement with knowledge of the orbit height of the satellite. Thus, any errors in the altimeter and orbit height measurements map directly into the sea surface height observables and reduce the ability to separate the desired ocean signal from the data. One of the many error sources in the altimeter process is the delay in the altimeter measurement caused by the charged particles in the Earth's ionosphere. For a 13.6 GHz altimeter, a Total Electron Content (TEC) of 1 TECU ( $10^{16}$  electrons/meter<sup>2</sup>) corresponds to approximately 0.218 centimeters of range delay. A maximum expected TEC (at solar maximum or during solar storms) of  $10^{18}$  electrons/meter<sup>2</sup> will create 22 centimeters of range delay. Since some ocean signals have centimeter level magnitudes, it is necessary to calibrate the ionosphere delay in the altimeter height measurements. If the radar altimeter transmits at two frequencies, a method involving a linear combination of the two signals (good to first order) can calibrate the delay to a sufficient level. However, use of a dual frequency altimeter increases the satellite cost, weight, and power consumption for altimetric missions. Several future missions, including the Navy's Geosat Follow-On (GFO) and NASA's TOPEX/Poseidon Follow-On (TPFO), are using or are considering using single frequency radar altimeters due to these constraints. Thus, a calibration of the ionosphere delay for altimeter height measurements to allow use of a single frequency altimeter is a subject of considerable interest.

This study was undertaken to investigate techniques with the potential of supplying a measure of the sub-satellite TEC at an accuracy requirement of 10 TECU (2.2 cm of range correction) for the purpose of correcting altimeter height measurements. This error limit is based on the accuracy requirement of the TOPEX/Poseidon mission, which is also the requirement imposed on GFO. TPFO, on the other hand, will have a requirement of 2.5 to 4 TECU (0.5 to 0.8 cm) based on the proven performance of the TOPEX/Poseidon mission (Calahan, 1994). Additionally, the 10 TECU accuracy for GFO needs only to be met in a global root mean square (rms) sense, while TPFO, in general, requires an instantaneous accuracy of less than 4 TECU over the ocean at all times.

Since climatological (monthly mean) models are known to be in error by as much as 50%, this work has primarily focused on the Parameterized Real-Time Ionospheric Specification Model (PRISM) which has the capability to improve TEC model accuracy by ingesting (adjusting to) *in situ* ionospheric measurements. The Global Positioning System transmits dual frequency L band signals that can be used to generate line-of-sight TEC measurements. For input into PRISM, these line-of-sight measurements must be mapped to the vertical direction. These line-of-sight measurements can also be processed to give global maps of vertical TEC in a sun-fixed frame (Mannucci, et al., 1993) that can also be ingested into PRISM. Thus two types of GPS data were used to adjust the PRISM model: GPS receiver station data mapped from line-of-sight observations to the

vertical at the intersection of the line-of-sight with the height of the ionosphere shell model at 350 km altitude, and a grid map (generated at the Jet Propulsion Laboratory) of GPS derived TEC data in a sun-fixed longitude frame (Mannucci, et al., 1993). The current International GPS (IGS) tracking network consists of over 40 globally distributed stations and thus provides an unprecedented global data set of ionospheric TEC data ideal for adjusting the PRISM model to improve sub-satellite TEC prediction (Melbourne, et al., 1991). Complementary work is being conducted at the Science Applications International Corporation (SAIC) using ionosonde data to adjust the PRISM model. Work is also underway at Hughes, STX, to modify the International Reference Ionosphere climatological model to allow it to ingest TEC data.

## Objectives

Because GPS is the only measurement system to offer a global data set of the ionosphere, this research has focused on evaluating the PRISM model, using global GPS TEC data as input, by comparing PRISM TEC predictions to TOPEX/Poseidon dual-frequency measurements of TEC (considered as truth). Additionally, for comparison, GPS derived TEC grids in a sun-fixed longitude frame and the climatological based International Reference Ionosphere (IRI-90) were investigated as independent TEC predictors. Thus, the primary objectives were to:

1. determine if adjusting the PRISM model with global GPS TEC (both the mapped vertical TEC and the TEC grid map) data results in sub-satellite TEC predictions that are accurate to within an rms error of 10 TECU, and, if the method cannot supply the required accuracy, to determine the reason;
2. investigate other techniques and data sets that could be used to improve the PRISM model prediction; and
3. evaluate and compare to other models and methods for predicting TEC, namely, the IRI-90 and the sun-fixed TEC grid maps.

## The Ionosphere

The ionosphere extends from about 60 km to between 500 and 2000 km above the surface of the Earth. It is composed of gas or plasma partially ionized by solar radiation and containing free electrons and positive ions such as to be electrically neutral. The ionosphere is generally divided into several layers, or regions, based on electron densities. Electron density influences electromagnetic wave propagation, in a frequency range of 100 MHz to 10 GHz, through free electron collision, electrical current flow, and reflection. From lowest in altitude to highest, the layers are the D region, which causes transmission attenuation, the E region, which primarily causes scatter and interference, and the F<sub>1</sub> and F<sub>2</sub> regions, which causes scintillation. The D, F<sub>1</sub> and F<sub>2</sub> layers vary with the solar cycle while the E layer varies with the 11-year sunspot cycle. The effect of each electron

density region, except for the  $F_2$  layer, essentially disappears at night when ionization occurs much less frequently. Representative plots of electron density versus altitude are given in figure 1 and demonstrate variations in electron density of orders of magnitude from day to night and over the complete solar cycle (Flock, 1983; Hanson, 1965).

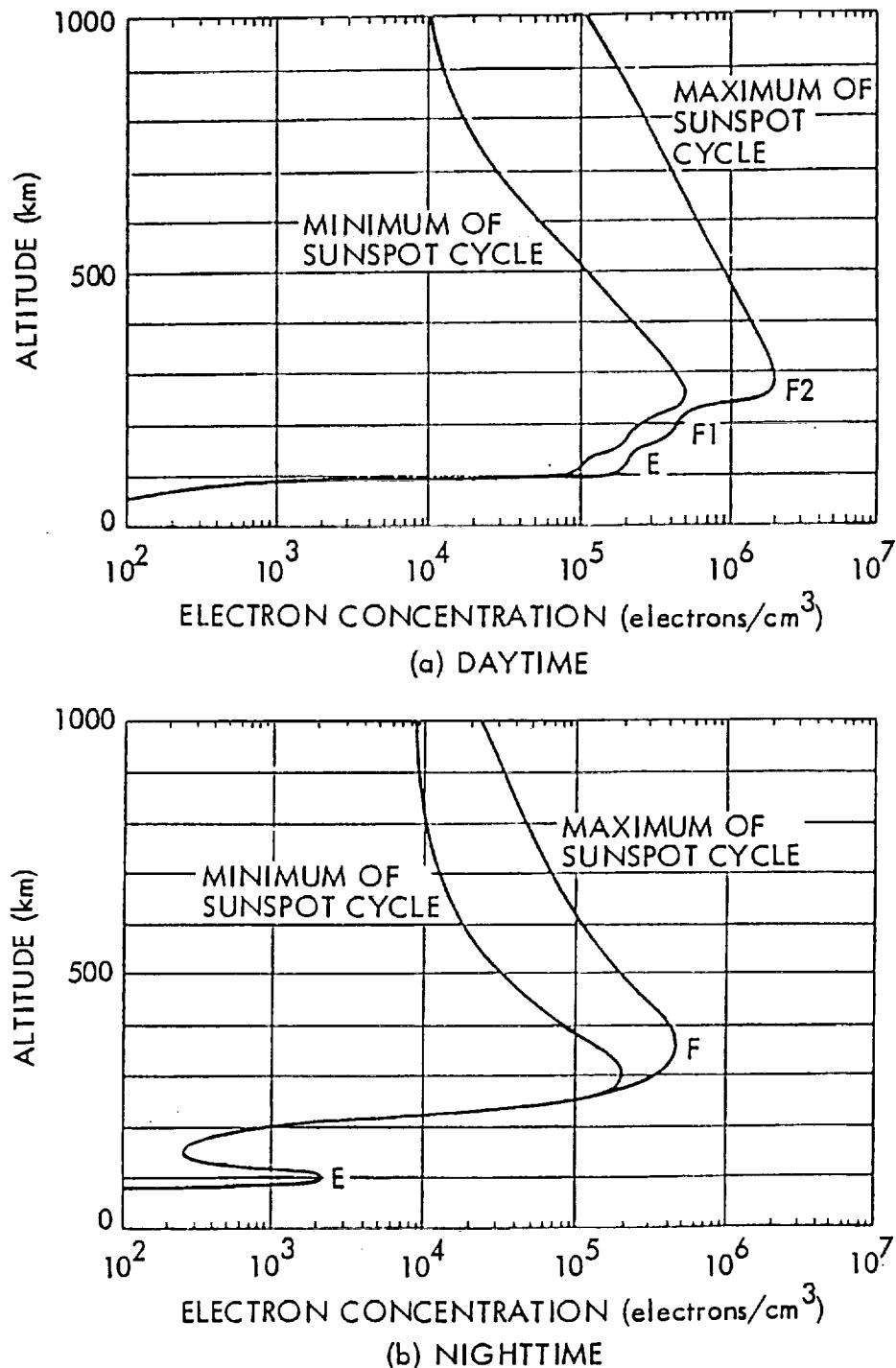


Figure 1. Daytime and nighttime electron density distributions at the extremes of the sunspot cycle (Hanson, 1965).

The ionosphere electron content varies temporally with solar cycle, sunspot cycle, and thermospheric winds, increasing with increased solar radiation. TEC is consequently higher during equinoxes, around solar maximum, and during the day, varying by factors of two seasonally, as much as five between solar maximum and minimum, and from three to eight during the day (Calahan, 1984). The electron content varies spatially due to intense electrical currents (electrojets), increased ionization at the geomagnetic equator and, to some extent, geomagnetic disturbances. Equatorial electrojets, driven by the Earth's magnetic field, cause an upward drift of ionization leaving a density gap at the equator, and a region of decreased density exists in the midlatitudes, most often at night, with a reduction in electron density of a factor of up to four (Calahan, 1984). Spatial and temporal effects are evident in Figures 6, 8 and 10, which sample the ionosphere over much of the Earth's latitudes at comparable times during the solar cycle, and will be discussed later.

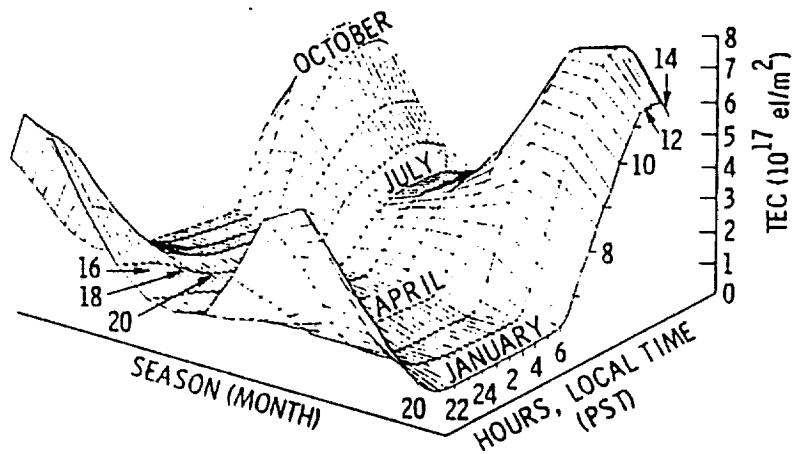


Figure 2. Monthly average total electron content profile for 1979 at Goldstone, California, as a function of time (Calahan, 1984).

## The Models

Several methods are available for modeling the ionosphere. These include climatological and physical models as well as interpolated data sets and global maps of TEC derived from GPS tracking network data. The latter of these has also been used to generate world-wide TEC grids by mapping GPS TEC data to a sun-fixed longitude reference frame.

IRI-90

The International Reference Ionosphere model, developed by the Committee on Space Research and the International Union of Radio Science (URSI), is the most

extensively researched climatological model and is highly regarded in the scientific community. IRI describes monthly averages of the electron density and temperature and ion temperature and composition in the altitude range from 50 km to 1000 km for magnetically quiet conditions in the non-auroral ionosphere (Bilitza, 1990). The model is based on interpolating data obtained from past and current ionosonde measurements, incoherent scatter observations, rocket ion mass spectrometers and various other data sets, as well as analytic functions developed to fill in the gaps. Combining several techniques and algorithms to interpret the data, IRI-90 generates interpolation equation coefficients for empirically determining the ionosphere composition from the atmospheric measurements to describe monthly mean vertical profiles for the main parameters of the ionosphere (Bilitza, 1990; Bilitza, 1993).

## PRISM

The Parameterized Real-Time Ionospheric Specification Model was developed for the United States Air Force (USAF) Air Weather Service by Computational Physics, Inc., of Newton, MA. The goal of the model is to provide a near real-time specification of the ionosphere over the entire globe. PRISM predicts the composition of the ionosphere using two models, an URSI model, which is a set of interpolation coefficients for empirical estimation of the ionosphere, and a physical model, which is based on parameterized physical models of the various layers of the ionosphere. The parameterized model uses both ground based and satellite based measurements of the ionosphere to adjust physical parameters to obtain a more accurate determination of the ionosphere. This adjustment procedure can correct eight profile parameters at the data locations. It also uses a weighting function, dependent on distance of the point of interest from the ingested data point, to specify a global correction field for the ionosphere. For single frequency altimeter calibrations, the goal is to ingest third-party ionosphere data, such as climatological or GPS TEC data into the PRISM model to more closely predict the actual sub-satellite TEC.

### The Parameterized Physical Model

There are four separate physical models that are used in PRISM to predict the state of the ionosphere. They are a low latitude F layer model, a mid latitude F layer model, a combined low and mid latitude E layer model, and a high latitude E and F layer model. For more details on these models see the PRISM 1.2 algorithm description (Daniell, Whartenby, and Brown, 1993). These four models have been parameterized in terms of geophysical parameters to achieve reasonable computational speeds. This parameterization process involved generating a set of databases for various values of the geophysical parameters. It also required the generation of semi-analytic representations of the databases. The authors of PRISM felt a model based on the theoretical physics of the ionosphere would perform better than climatological models when ingesting ionospheric measurements.

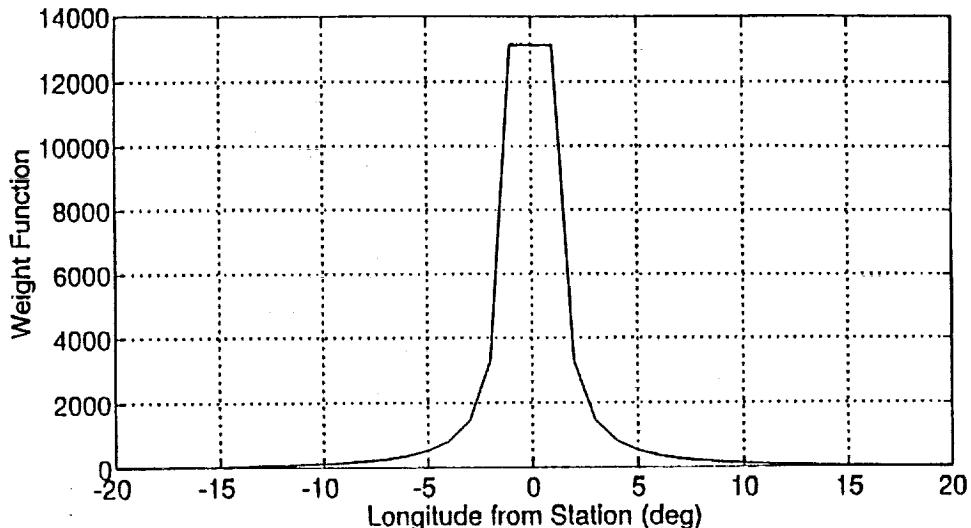


Figure 3. Original PRISM weight function versus longitude at the equator. This function essentially de-weights any data more than three degrees away from the measurement site.

#### Adjustment Procedure

PRISM employs a real-time adjustment procedure which enables it to adjust the parameterized physical model using a variety of ionosphere data. These data types include: bottomside soundings ( $f_o F_2$ ,  $h_m F_2$ ,  $f_o E$ ,  $h_m E$ ) of the Digital Ionosphere Sounding System (DISS), TEC data from any source, and *in situ* plasma and auroral electron and ion fluxes from the DMSP satellites. Before any real-time adjustment, PRISM uses linear interpolation on  $F_{10.7}$  and  $K_p$  to obtain the best prediction of the ionosphere from the parameterized databases. Once the most accurate state of the ionosphere is generated from the databases, the real-time adjustment procedure uses the available data to correct for eight profile parameters at each data site. In between each measurement site, as will often be the case for the altimeter application, a weighted average based on distance is used to interpolate the eight adjustment parameters. Figure 3 shows the original weight function used in the PRISM adjustment procedure. This function ensures that PRISM will match the data at each measurement site and that TEC will vary smoothly between sites. The large drop off of this function also ensures that information from a site will not be used relatively far ( $> 500$  km) from a site. This function is, however, somewhat deceiving. For example, if the point of interest is far away from the TEC data source, the weight function will form a weighted average of all the data sources. Therefore, TEC data from any site can influence predictions of TEC at distances much greater than 500 km. For this analysis, GPS TEC data were used to adjust the PRISM model.

## Global GPS TEC Data

The current International GPS Service (IGS) tracking network consists of almost 45 globally distributed stations (Figure 4) and provides an unprecedented global data set

of ionospheric TEC which will undoubtedly contribute to a better understanding of the Earth's ionosphere (Melbourne et al., 1991). However, this 45 station network, as with most tracking networks, does have a shortage of stations in the southern hemisphere, near the equator and also over the ocean. Fortunately, the IGS plans to add additional stations to the network by 1995 to fill in some of these gaps. The configuration used in this study was the 35 station network that was available for March of 1993 (Figure 5).

Deriving GPS TEC data that is suitable for input into the PRISM model is a rather complicated process. Measurements from the Global Positioning System consist of two L band signals (L1 at 1575.42 MHz and L2 at 1227.6 MHz) that in theory can be linearly combined in a straight forward manner to compute a measure of the TEC between the GPS satellite and the GPS receiver. In practice, however, this computation is complicated by the presence of hardware biases between the L1 and L2 channels in both the GPS satellite and the receiver. Thus, to derive an absolute measure of line-of-sight TEC, these biases must be solved for (or calibrated if possible) and removed from the data. Once an absolute measurement of line-of-sight TEC is formed, it must be mapped to an equivalent vertical TEC which can be ingested by PRISM.

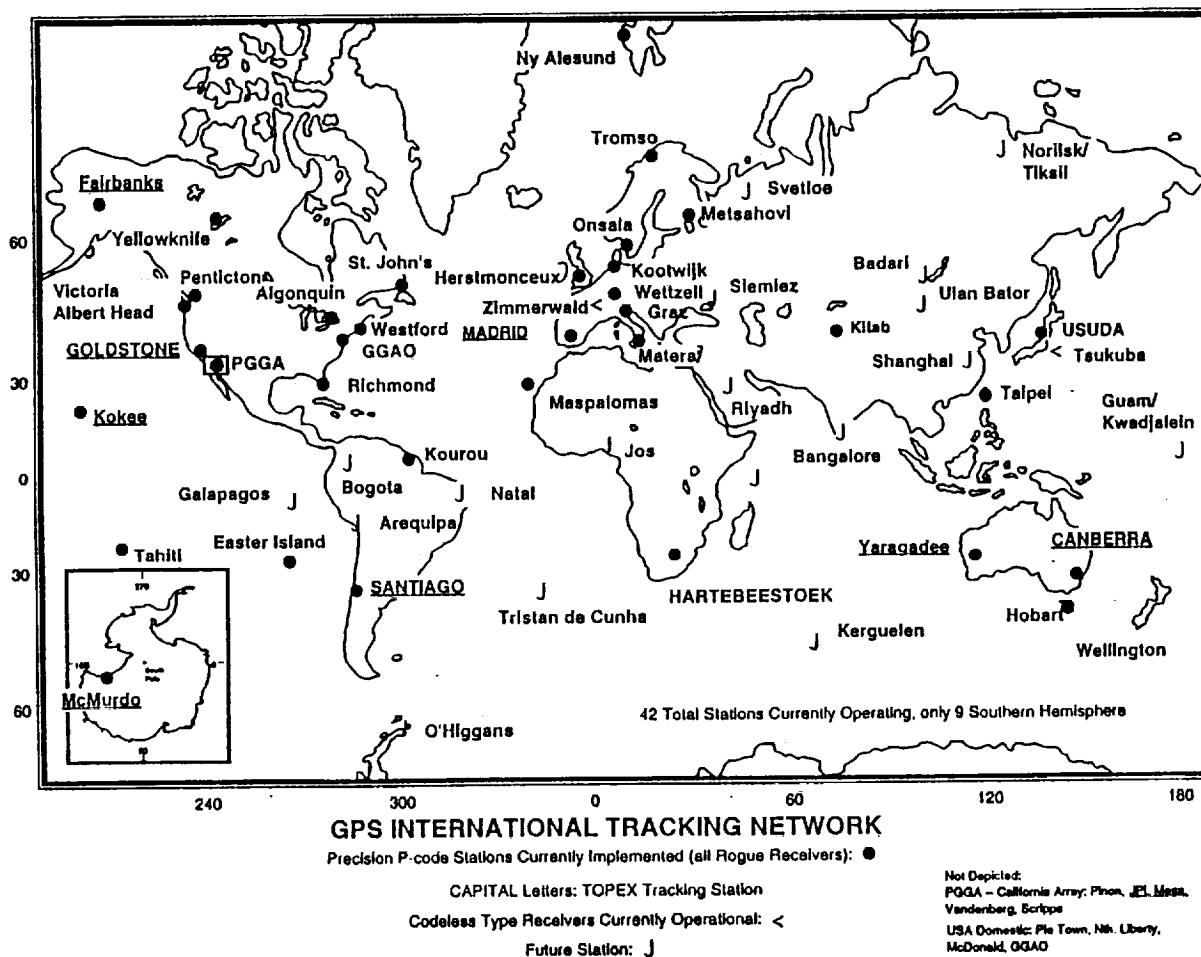


Figure 4. Current IGS tracking network with future planned stations. Courtesy of Ruth Neilan, JPL, 1993.

The first step in the procedure (to generate absolute vertical TEC data) is to form the biased line-of-sight TEC data from the raw dual frequency measurements. A dual frequency GPS receiver outputs pseudorange (less precise) and carrier phase (very precise) on both the L1 and L2 frequency at each observation time step. A biased measure of TEC can be computed from the pseudorange data based on the pseudorange measurements at the two frequencies. Because pseudorange is an absolute (but noisy) range measurement, the pseudorange derived TEC is a noisy measure of TEC with only the satellite and receiver L1/L2 hardware biases included. The carrier phase gives only a very precise measure of change in TEC over an arc, because it is biased by an unknown number of L1 and L2 cycles. By performing a least squares fit (or leveling) of the carrier phase TEC data to the pseudorange TEC data over a pass, a precise line-of-sight TEC measurement biased only by the receiver and satellite hardware biases (and not the carrier cycle ambiguities) can be generated. This is given by  $TEC_{measured} = TEC_{true} + b_{sat} + b_{rcvr}$ , where  $b_{sat}$  and  $b_{rcvr}$  are the satellite and receiver biases, respectively.

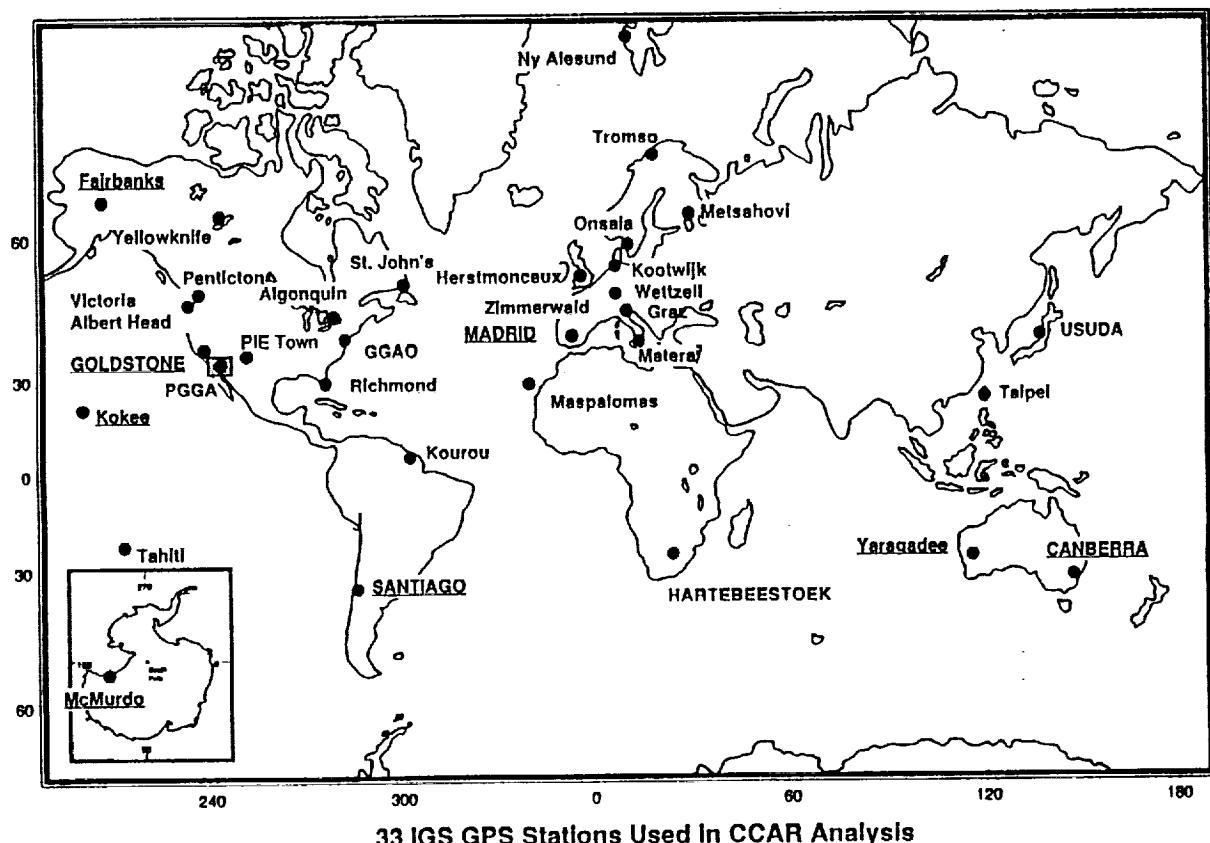


Figure 5. IGS tracking network 33 station configuration available in March 1993 and used for this study. Courtesy of Ruth Neilan, JPL, 1993.

The next step of this procedure is to remove the L1/L2 receiver and satellite hardware biases,  $b_{sat}$  and  $b_{rcvr}$ . Some of the IGS network GPS Rogue receivers have the capability to perform a calibration measurement of their receiver bias. However, many of the receivers do not have this capability, and the GPS satellites can not perform this type of calibration. Fortunately, the same technique currently being studied at JPL to estimate

the global grid of TEC also provides a means of estimating both the satellite and receiver L1/L2 biases (Mannucci, et al., 1993). The biases are estimated as constants along with the grid TEC values. These estimated hardware biases or receiver calibrated biases can be subtracted from the TEC measurements to obtain absolute measurements of line-of-sight TEC from the receiver to the GPS satellite.

Once the absolute line-of-sight TEC data have been formed, they are mapped to the vertical using an infinitely thin ionosphere shell assumption (Lanyi and Roth, 1988). The line-of-sight TEC is mapped to the vertical at the intersection of the measurement and the thin ionosphere shell. Thus, for a given receiver and a given time, there will be a number of vertical TEC measurements that have been mapped to varying sub-ionospheric latitude and longitude intersection points. This is one form of the TEC data that was input into PRISM in this analysis.

The uncertainties in the derived vertical GPS TEC data are composed of both random and systematic effects. These errors can be attributed to measurement noise in the original carrier phase data, uncertainties in the least squares fits between the pseudorange and carrier phase data, and uncertainties in the L1 and L2 receiver and satellite biases determined by hardware calibrations or estimated by the JPL technique. An estimate of the uncertainty in the line-of-sight absolute GPS TEC measurements depends on which set of receiver biases are used. If a receiver hardware calibration is used (If GPS receiver hardware calibrations were available, they were used instead of the bias estimates.), a GPS TEC measurement uncertainty can be obtained by performing a root sum square (rss) operation on the pseudorange and carrier phase least squares fit uncertainty (0.5 to 1.0 TECU), the GPS satellite bias estimate formal uncertainty (0.8 to 0.9 TECU), and the expected uncertainty of the hardware calibration (0.3 TECU) to yield a combined rss uncertainty in the range of 1.0 to 1.7 TECU. If an estimate of the receiver bias is used, a total GPS TEC measurement uncertainty can again be obtained by performing the rss operation on the pseudorange and carrier phase least squares fit uncertainty, the GPS satellite bias estimate formal uncertainty, and the uncertainty of the receiver bias estimate (0.8 to 2.5 TECU) to give a combined rss expected uncertainty ranging from 1.2 TECU to 2.8 TECU. The maximum expected vertical GPS TEC data uncertainties can be obtained by dividing the line-of-sight uncertainties by a mapping function, essentially a simplification, value of 2.2 at 20 degrees elevation (Lanyi and Roth, 1988) to give maximum uncertainties of 0.76 TECU rms when using receiver hardware calibrations and 1.14 TECU rms when using estimates of the receiver biases. (These uncertainties do not include errors due to the vertical mapping process.) These worst case maximum vertical GPS TEC data uncertainties are still well below the desired ionospheric correction requirement of 10 TECU rms.

## Grid Maps

Using tracking data from the GPS network, a group at the Jet Propulsion Laboratory (JPL) has developed a means of processing data from ground based GPS receivers to generate a 642 point global hourly grid of vertical TEC and uncertainty in a sun-fixed longitude reference frame (Wilson, et al., 1992; Mannucci, et al., 1992;

Mannucci, et al., 1993). This is accomplished by taking mapped vertical GPS TEC data over a 24 hour period and rotating it in longitude (by the amount that the Earth has rotated through in that time) to the sun-fixed frame. Zero hour sun-fixed longitude has been defined as 12 hours GMT for Greenwich longitude. This data is then processed to give estimates of the TEC associated with each grid point. Additionally, the process estimates the GPS satellite and GPS receiver biases as constants which is needed for calculating absolute TEC from the GPS data.

The grid consists of a network of stochastic (random walk) points in time that are updated (along with their covariances) hourly as new GPS TEC data are acquired. If GPS TEC data are not present over a grid point, the estimate of the grid point is not updated at that time, and its uncertainty increases according to the noise assigned to the stochastic parameter. Thus, the technique provides both a grid estimate as well as a corresponding covariance (reflecting the estimate uncertainty) of TEC in a sun-fixed frame. The TEC and covariances at each grid point are interpolated to a one-by-one degree resolution map to give estimates globally at every longitude and latitude point. The accuracy of the TEC grid maps depend greatly on the distribution of the GPS ground receivers, and until the complete network is installed the coverage remains sparse over some regions, particularly high latitudes, near the equator, and over the oceans. However, because the model is developed in a sun-fixed frame as a function of time (*i.e.*, grid maps every hour), near global coverage can be attained. The accuracy is not as much limited by the spatial decorrelation of the ionosphere as it is by the temporal correlations of the ionosphere (over a few hours) and the coverage by the GPS receivers.

## TOPEX Dual Frequency TEC Data

The TOPEX/Poseidon altimeter may be the most precise TEC measurement system available. The TOPEX/Poseidon project at the JPL distributes geophysical data records that contain all relevant altimetric data, including the dual frequency ionospheric TEC measurements in the form of range correction. Deriving sub-satellite TEC data from the TOPEX/Poseidon dual frequency altimeter is less complicated than deriving GPS TEC data, but is still not straight forward. Measurements from the TOPEX/Poseidon altimeter consist of round trip light times of both the Ku and C band signals (13.6 and 5.3 GHz) off the ocean surface. In theory, these measurements can be used directly to compute the TEC between the altimeter and the ocean surface. However, similar to the GPS TEC procedure, this computation is complicated by the presence of a hardware bias between the Ku and C band channels. Thus, to derive an absolute measure of line-of-sight TEC, these biases must be removed from the data. Fortunately, the Ku and C band relative offset was estimated (at about 1.7 cm, or an 8 TECU effect) by the TOPEX/Poseidon project at the JPL using histograms of the ionosphere TEC data (Calahan, personal communication, 1993). Besides accounting for the channel biases, other corrections that are applied to the TOPEX/Poseidon TEC data include estimates of the pointing angle errors and varying Ku and C band sea state (*i.e.*, electromagnetic bias) effects.

The uncertainties in the derived TOPEX/Poseidon TEC data comprise both random and systematic effects. The random measurement noise in the TOPEX/Poseidon TEC data is due to the noise of the Ku and C band range measurements. The error due to noise on the Ku and C band range measurements is approximately 2.3 TECU rms. The systematic errors are more difficult to quantify, although it is believed that the 10 cm relative Ku and C band offset is accurate to approximately 2 cm (Calahan, personal communication, 1993). This 2 cm uncertainty corresponds to an error of about 1.8 TECU (0.4 cm at Ku band). Not considering the error caused by the differing band electromagnetic biases (which vary with sea state and are difficult to bound), an optimistic estimate of the uncertainty of the TOPEX/Poseidon TEC data can be computed by taking the root sum square of the random measurement noise and the uncertainty of the relative Ku and C band offset giving a value of 2.9 TECU which is much smaller than both the worst case GPS TEC data uncertainty (5.5 TECU) and the ionospheric correction requirement (10 TECU).

## Results

A set of globally distributed TEC measurements were generated using GPS data (acquired from JPL) for March 12, 1993 for input into PRISM. Post-processed estimates of solar and geophysical data were obtained from the National Geophysical Data Center in Boulder, Colorado, to allow the PRISM unadjusted base model to be as accurate as possible. March 12, 1993 was a moderately active day with an  $F_{10.7}$  and sun spot number of 158.7 and 77.0, respectively. The PRISM parameterized model was used to generate adjusted and unadjusted TEC values for a number of TOPEX/Poseidon sub-satellite tracks in cycle 18 for this day.

The following results compare the PRISM adjusted (with only the raw GPS TEC data) and unadjusted values with the TOPEX/Poseidon TEC data for a one minute time step. The TOPEX/Poseidon TEC one second data was smoothed over 20 seconds centered around each one minute time interval. A smoothing interval of 20 seconds was found to be optimal by the TOPEX/Poseidon project office at JPL (Calahan, 1994). The data is presented by showing the adjusted and unadjusted PRISM TEC values and the smoothed TOPEX/Poseidon TEC values versus time along the TOPEX/Poseidon ground track. The rms differences between the adjusted and unadjusted PRISM TEC curves and the TOPEX/Poseidon curve are also shown. Figure 6 is a groundtrack plot of TOPEX/Poseidon pass 43 showing the relative geometry between the passes and the closest GPS TEC sites at a local time of approximately 1 am. Figure 7 is a plot of the TOPEX/Poseidon and PRISM TEC values for pass 43 and shows very little improvement when ingesting raw GPS TEC data, as verified by the identical 5.3 TECU rms differences for the adjusted and unadjusted PRISM values. Even though the rms error does not reflect it, the PRISM values are adjusted significantly by the GPS TEC data. There is a noticeable jump in the adjusted PRISM TEC between the 6th and 7th data points (each point is one minute of time in the pass) due to the fact that PRISM changes from the high-latitude ionosphere adjustment procedure to the mid-latitude procedure, which uses the

GPS TEC data differently. Additionally, the station in Tahiti improves the PRISM TEC values near its point of closest approach (PCA), but is too far away to help the TEC adjustments where the TOPEX/Poseidon TEC is near 35 TECU (at 32500 seconds). There also is a near overflight of a California site, but the TEC at this time (during a night time ionosphere) is too small to notice a significant adjustment.

The next four figures show TOPEX/Poseidon passes 52 and 54, which traverse the day time ionosphere near local noon. Figures 8 and 9 show the groundtrack and PRISM results for pass 52. A significant rms improvement for pass 52 is shown in Figure 9. The decrease from 12.7 TECU to 8.5 TECU when using the GPS TEC data is caused by close TOPEX/Poseidon overflights with the GPS sites. The GPS site in Richmond, Florida, aids the PRISM adjustment in the beginning of the pass, and the site in Santiago, Chile, improves the adjustment in the middle. Figures 10 and 11 show the groundtrack and results for pass 54. This pass traverses the maximum of the daytime ionosphere where the TOPEX/Poseidon altimeter measured TEC as high as 120 TECU. There is a slight improvement in the PRISM TEC values when using GPS TEC data, but the rms difference (15.5 TECU) is still well above a 10 TECU requirement, with data excursions of as much as 40 TECU (8 cm at Ku band). Again, this is because there are no stations in the vicinity of the pass when it enters the maximum ionosphere.

These results demonstrate that the PRISM adjustment procedure does well at matching the TOPEX/Poseidon TEC values when the TOPEX/Poseidon overflight point is near a GPS TEC measurement. This is because the PRISM weight function used in the adjustment procedure only incorporates most of the information from a TEC measurement 300 to 400 km away from that measurement. Because of this, the authors modified the weight function to incorporate the TEC measurement information at distances up to 1000 km away from the measurement, understanding that this may have enabled some decorrelated information to be used. PRISM was run again over the same three passes using the modified weight function and generated rms differences of 7.1 TECU, 6.9 TECU and 14.4 TECU, respectively, compared with the original weight function rms differences of 5.3, 8.5 and 15.5 TECU. Passes 52 and 54 showed only modest improvement while pass 43 results actually degraded. These results are inconclusive, but they do show that using a weight function with a larger decorrelation distance does not give appreciably better results and could make the adjustments worse in areas with high TEC gradients.

At this point, the weighting function used by PRISM was modified again for ingesting JPL grid map TEC data according to the expected accuracy of the TEC prediction. This would allow weighting the JPL grid data with the uncertainties associated with each grid point. The affect of the weighting would be to adjust with the grid data if the uncertainty is small and to make less of an adjustment for the grid data if the uncertainty is large. The weighting function was optimized by minimizing the rms differences between the PRISM TEC predictions and TOPEX/Poseidon TEC measurements over the entire day.

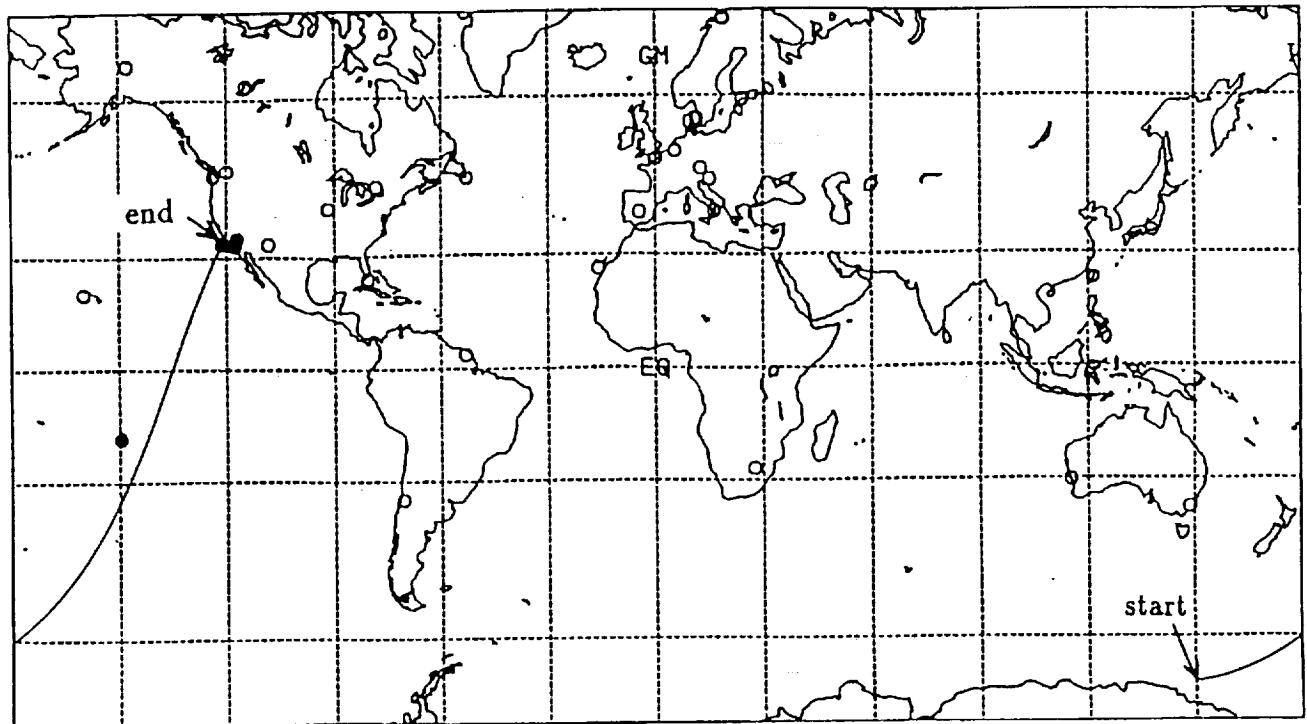


Figure 6: TOPEX groundtrack for pass 43 (cycle 18) with nearby IGS GPS stations (black dots).

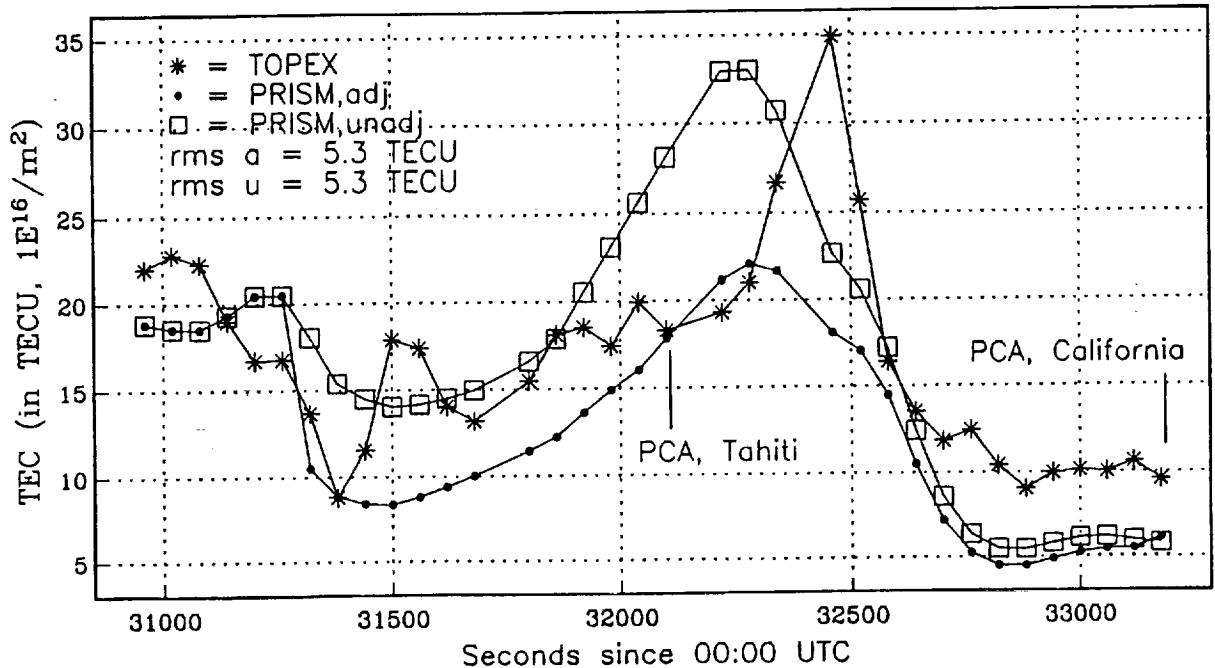


Figure 7: TEC Data (March 12, 1993) for TOPEX pass 43 (cycle 18) - rms differences between PRISM adjusted and unadjusted TEC and TOPEX TEC measurements. Local time at midpoint of pass is approx. 1 am.

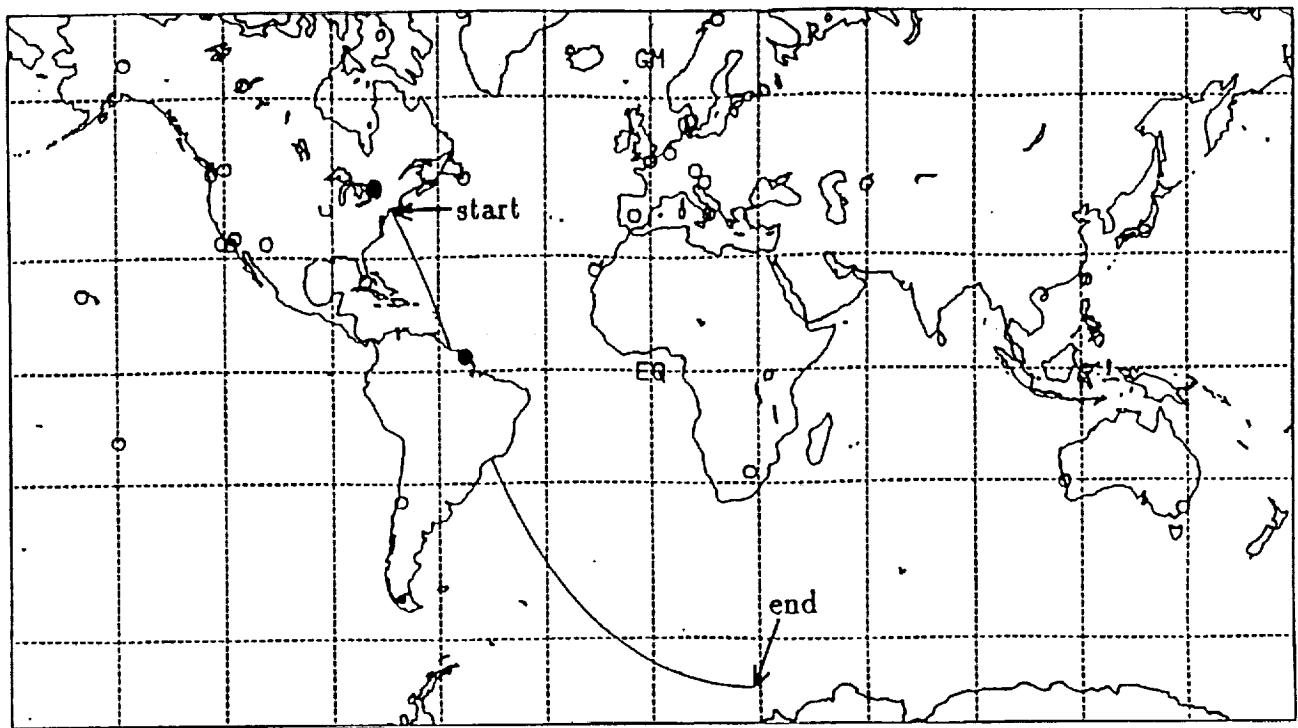


Figure 8: TOPEX groundtrack for pass 52 (cycle 18) with nearby IGS GPS stations (black dots).

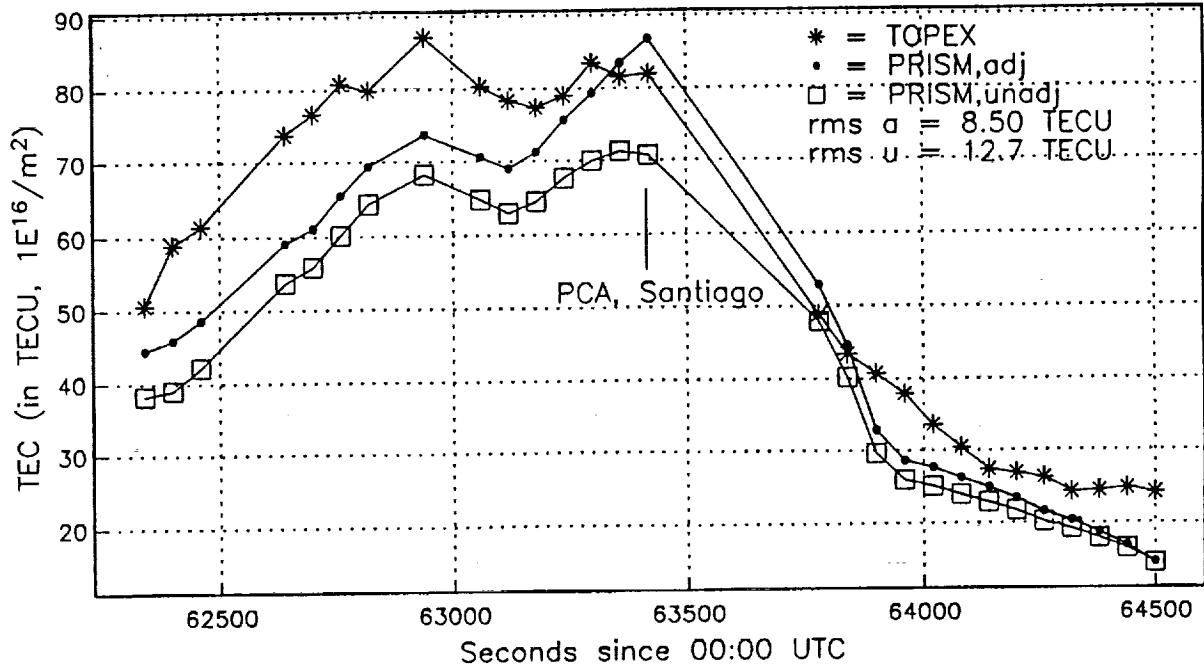


Figure 9: TEC Data (March 12, 1993) for TOPEX pass 52 (cycle 18) - rms differences between PRISM adjusted and unadjusted TEC and TOPEX TEC measurements. Local time at midpoint of pass is approx. 12 noon.

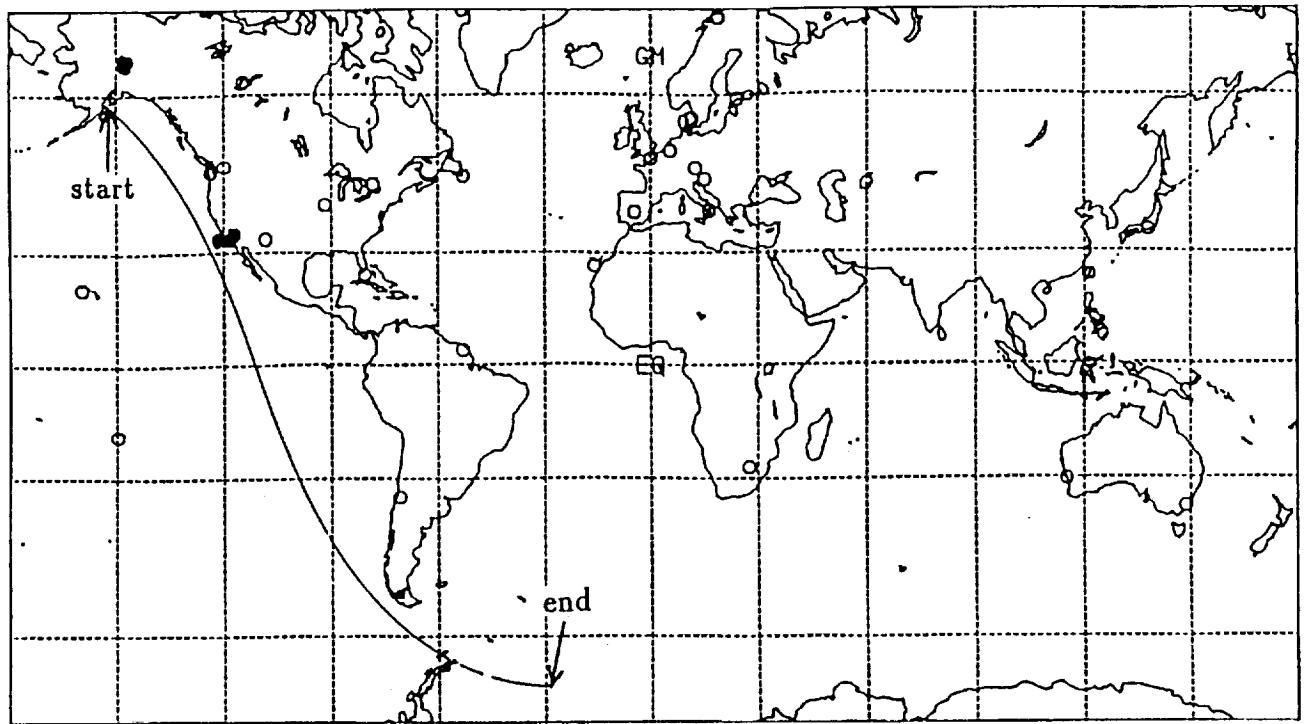


Figure 10: TOPEX groundtrack for pass 54 (cycle 18) with nearby IGS GPS stations (black dots).

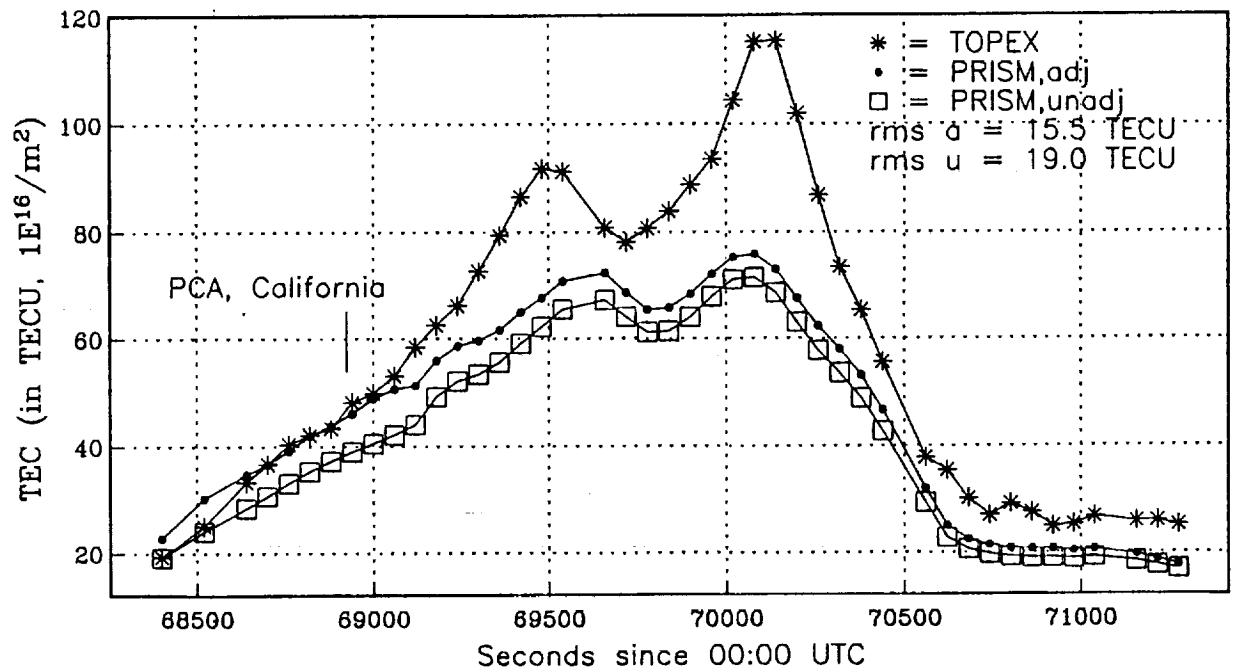


Figure 11: TEC Data (March 12, 1993) for TOPEX pass 54 (cycle 18) - rms differences between PRISM adjusted and unadjusted TEC and TOPEX TEC measurements. Local time at midpoint of pass is approx. 12 noon.

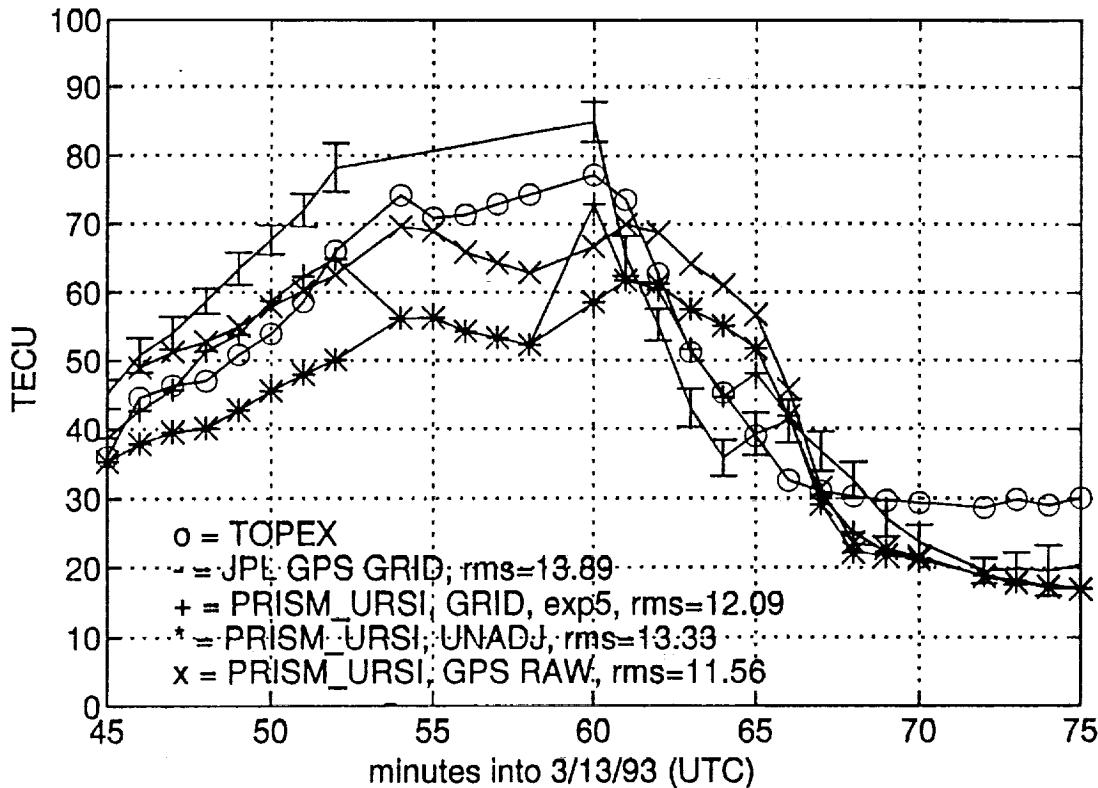


Figure 12: Smoothed TEC comparisons of PRISM URSI models against TOPEX TEC, cycle 18, pass 60 (midpoint local time is approx. noon).

Both the unadjusted parameterized and empirical URSI PRISM models were used to generate TEC values for comparison with TOPEX/Poseidon dual-frequency TEC measurements for all of the TOPEX/Poseidon sub-satellite tracks in cycle 18 on March 13, 1993 (the reason for the change in day of interest was because the only JPL TEC grid map data available was centered on March 13). The models were then adjusted separately with the raw GPS TEC data using the original PRISM weighting function and with the JPL TEC grid data using the optimized weighting function over the same satellite tracks. Finally, for comparison, TEC predictions were obtained by a fully climatological prediction using IRI-90 and by using the JPL sun-fixed grid maps as a stand-alone means for generating interpolated TEC predictions over the period of interest.

Each of these model variations was run over the entire day. However, the only figures presented here are for pass 60 (Figures 12-14), a relatively active data set in which straight forward comparisons could be made, and rms errors for this pass are shown in Table 1. Tables 2-3 show the performance of each of the predictions for the entire day. The following results compare the PRISM adjusted (with raw GPS TEC data as well as JPL grid data) and unadjusted values for the URSI and parameterized models, smoothed at one minute intervals, with the TOPEX/Poseidon TEC data, IRI-90 climatological data, and the interpolated data from the unmodified JPL grid map itself. The data is presented by showing the adjusted and unadjusted PRISM TEC values and the smoothed TOPEX/Poseidon TEC values versus time along the TOPEX/Poseidon ground track.

Model	mean (TECU)	rms (TECU)
PRISM, ursi, JPL GPS grid	-8.15	12.09
PRISM, ursi unadjusted	-10.22	13.33
PRISM, ursi, vertical GPS (raw)	-5.22	11.56
PRISM, par, JPL GPS grid	-8.08	12.31
PRISM, par unadjusted	-11.56	14.15
PRISM, par, vertical GPS (raw)	-10.98	14.23
JPL GPS grid (2-sigma)	-5.01	13.89
IRI-90	4.74	11.55

Table 1: Comparisons with TOPEX TEC, 13 March 1993, cycle 18, pass 60 (midpoint local time is approx. noon).

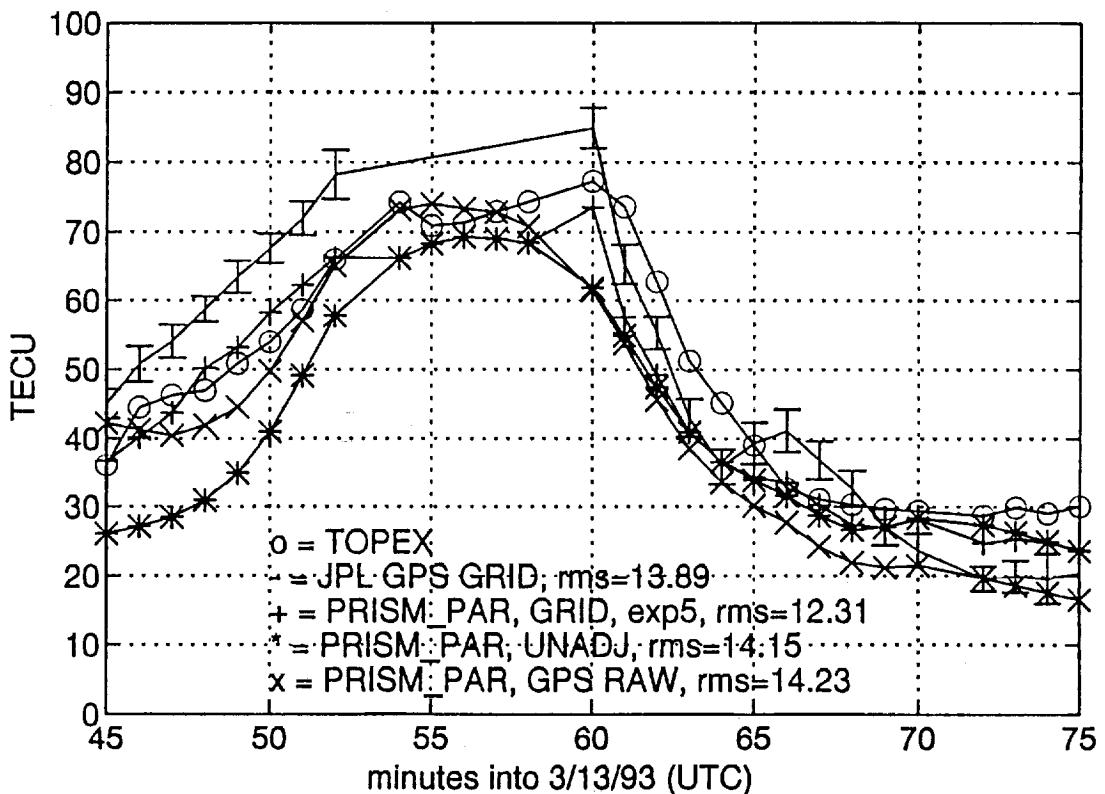


Figure 13: Smoothed TEC comparisons of parameterized PRISM models against TOPEX TEC, cycle 18, pass 60 (midpoint local time is approx. noon).

Figure 12 shows the predictions of the PRISM URSI model unadjusted, adjusted with the JPL grid using the optimized weighting function, and adjusted with the raw vertical GPS TEC data and original weighting function. The TOPEX/Poseidon data and the JPL grid map data, with uncertainty bars, are also shown. PRISM URSI adjusted with the raw GPS data visibly performed the best, having the same general structure and comparable TEC estimates as the TOPEX/Poseidon track. The model adjusted with JPL grid data started out well, but developed significant errors when the uncertainties in the JPL grid became unreasonably large causing the model between 52 to 60 minutes to revert

back to the base model. Table 1 presents the rms and mean differences between the predictions by each model and the TOPEX/Poseidon data.

Figure 13 gives the predictions of the PRISM parameterized model for the same three cases of adjustment. For this PRISM base, the model adjusted with the JPL grid data conformed best to the general structure and estimation of the TOPEX/Poseidon track. For further comparison, Figure 14 shows both of the PRISM base model predictions against the TOPEX/Poseidon track and the IRI-90 TEC estimates for the data set. The rms errors and mean deviations of the parameterized model predictions also are given in Table 1. From these errors, it is obvious that during a daytime ionosphere none of the methods predict TEC very accurately. The figures indicate that almost all of the models underpredict the TOPEX/Poseidon TEC and some have difficulty in modeling even the general structure of the ionosphere.

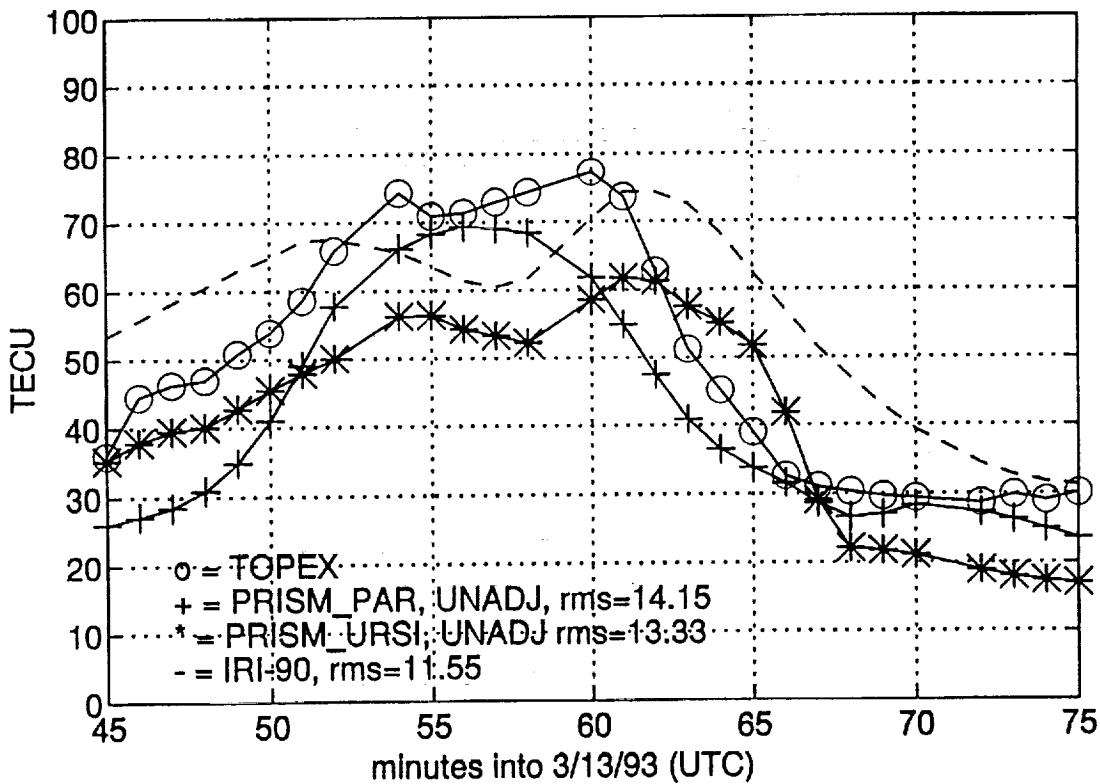


Figure 14: Smoothed TEC of unadjusted parameterized and URSI PRISM models compared against IRI-90 and TOPEX TEC for cycle 18, pass 60 (midpoint local time is approx. noon).

Over the complete length of the day, passes 60-84, the rms values were computed for each of the base and adjusted models for ascending and descending passes and are given in Tables 2 and 3 along with total daily values. From this information it is clear that the PRISM URSI model adjusted with the raw vertical mapped GPS TEC data was the most accurate in terms of mean and rms TECU differed with the TOPEX/Poseidon data, and is the only model that meets a 10 TECU accuracy requirement during a daytime

ionosphere. These TEC predictions by the PRISM URSI model adjusted with raw vertical mapped GPS TEC data were differenced from the TOPEX/Poseidon TEC measurements at each latitude (and corresponding time) over every available pass in the day, and the differences are plotted separately for a daytime ionosphere (descending passes, Figure 15) and a nighttime ionosphere (ascending passes, Figures 16). It is seen that 20 TECU differences are common. These will translate into 3-4 cm errors in sea surface height if the PRISM URSI model is used to correct altimeter data. Although the TEC predictions from the JPL grid by itself are given, the fact that the GPS coverage exhibits huge uncertainties over large areas lends little reliability to the grid alone as a global TEC predictor.

Method	mean (TECU), ascending	rms (TECU), ascending	mean (TECU), descending	rms (TECU), descending
PRISM, ursi unadjusted	-7.22	12.47	-10.44	14.11
PRISM, par, unadjusted	-2.19	8.79	-9.00	14.71
<b>PRISM, ursi, GPS raw</b>	<b>-2.22</b>	<b>8.60</b>	<b>-3.96</b>	<b>9.74</b>
PRISM, par, GPS raw	-3.64	8.33	-8.23	14.00
PRISM, ursi, JPL GPS grid	-5.93	10.87	-8.73	12.69
PRISM, par, JPL GPS grid	-3.63	8.47	-7.57	12.83
IRI-90	5.86	11.19	5.23	13.16

Table 2: Comparisons with TOPEX TEC, 13 March 1993, cycle 18, complete day, passes 60-84; ascending passes (odd numbered, nighttime) and descending passes (even numbered, daytime) separated.

Method	mean (TECU)	rms (TECU)
PRISM, ursi unadjusted	-8.8	13.3
PRISM, par, unadjusted	-5.6	12.1
<b>PRISM, ursi, GPS raw</b>	<b>-3.1</b>	<b>9.2</b>
PRISM, par, GPS raw	-5.9	11.5
PRISM, ursi, JPL GPS grid	-7.3	11.8
PRISM, par, JPL GPS grid	-5.6	10.9
IRI-90	5.5	12.2

Table 3: Comparisons with TOPEX TEC, 13 March 1993, cycle 18, complete day, passes 60-84

One thing to note regarding the PRISM predictions is that the average TECU difference for almost every method is negative, indicating that the models are consistently underpredicting the TOPEX/Poseidon TEC measurements. One possible contributing factor is a bias of as much as +1 cm (5 TECU), found recently by the TOPEX/Poseidon Project Office in the TOPEX/Poseidon measurement data (Imel, 1994; Calahan, personal communication, 1994). Accounting for this bias would certainly decrease the mean deviation of the model predictions and, to an extent, bring down the rms errors as well.

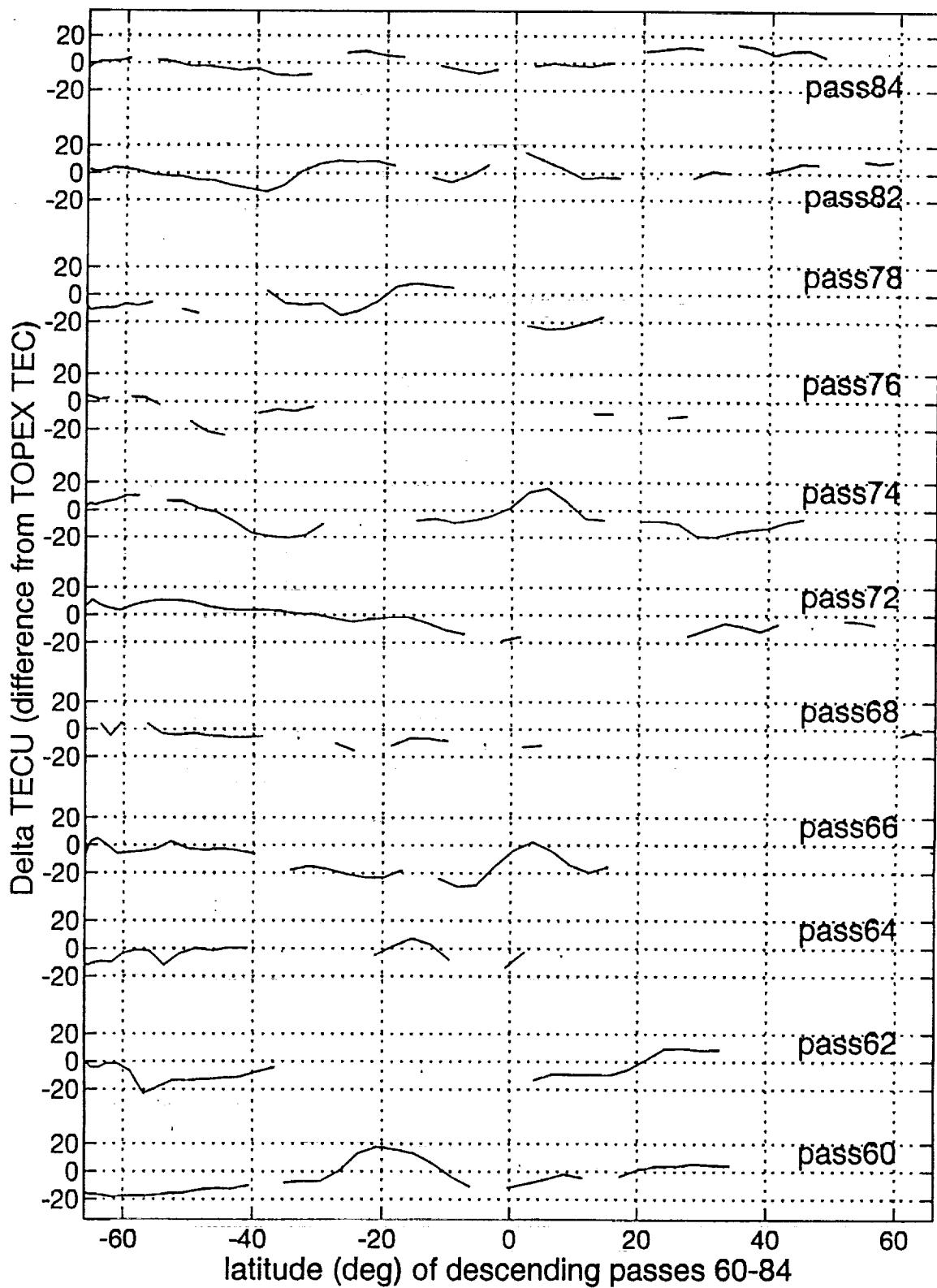


Figure 15: PRISM URSI TEC (March 13, 1993) for TOPEX cycle 18, daytime (descending passes).

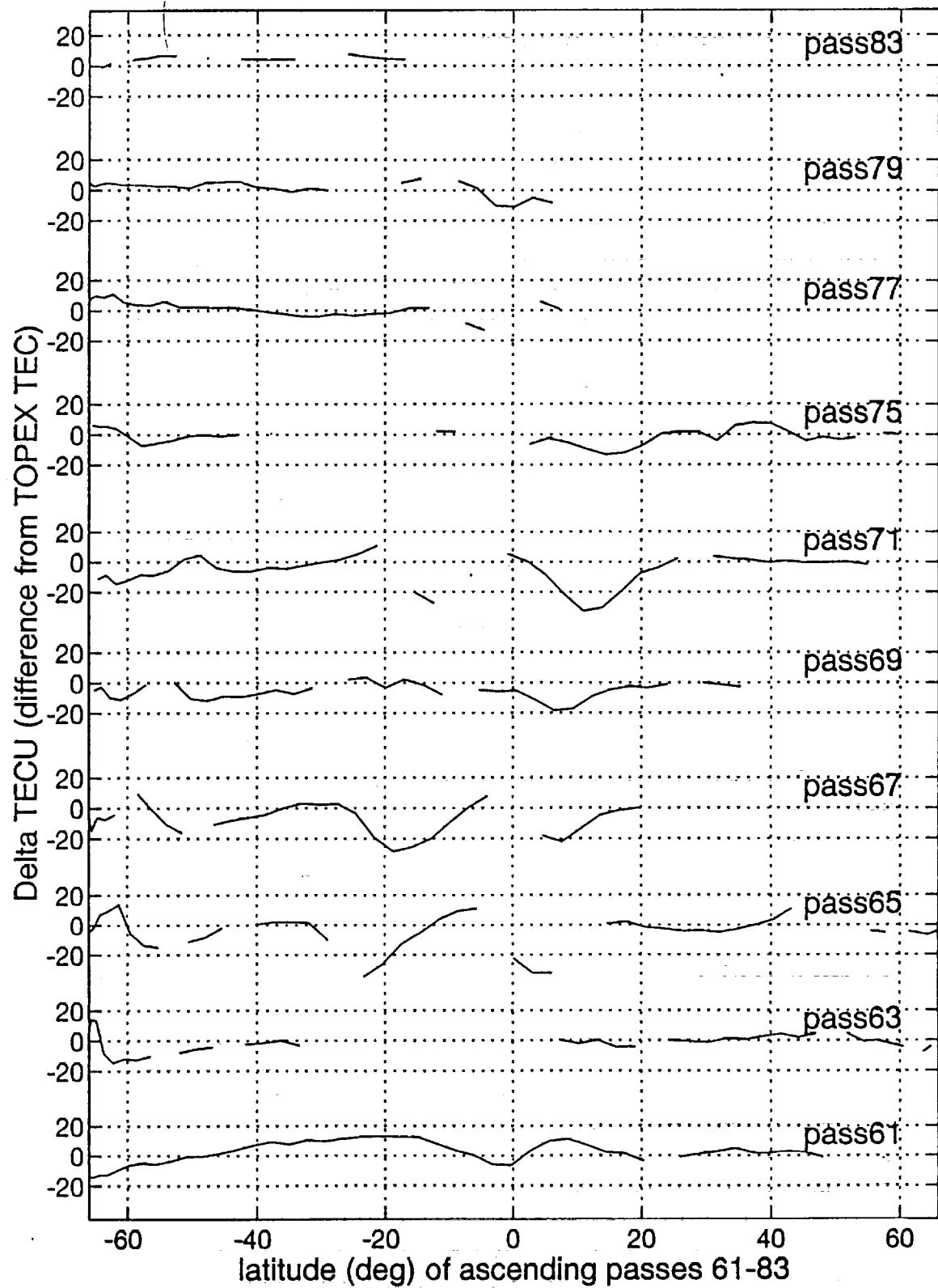


Figure 16: PRISM URSI TEC (March 13, 1993) for TOPEX cycle 18, nighttime (ascending passes).

## Discussion and Conclusions

The adjusted PRISM values generally compared to the TOPEX/Poseidon measurements within a 10 TECU accuracy requirement when the sub-satellite track passed within 300 to 400 km of the GPS TEC data or when the track passes through a night time ionosphere. However, when the sub-satellite points were greater than 300 to 400 km away from the GPS mapped vertical TEC data or when a local noon ionosphere was sampled, the adjusted PRISM values generally differed by greater than 10 TECU with data excursions from the TOPEX/Poseidon TEC measurements of as much as 40 TECU (an 8 cm error at Ku band). A modified weight function (using information at distances up to 1000 km away from the GPS TEC data) was studied and showed no appreciable improvement in the PRISM adjustment procedure. Therefore, it may be concluded from this analysis that ingesting TEC data from the current set of GPS stations directly into PRISM will not predict sub-satellite TEC at the 10 TECU rms level everywhere in a daytime ionosphere. Because the PRISM adjustment procedure generally incorporates information from measurements that are within 300 to 400 km (derived from the inherent spatial decorrelation distance of the ionosphere) of the TOPEX/Poseidon overflight point, a prohibitively large number of ionospheric measurement sites would be needed as input to PRISM to consistently meet a 10 TECU accuracy requirement.

The performance of PRISM using JPL grid data is promising, considering this technique has only recently been developed and should show marked improvement when the IGS network is completed. It is the opinion of the authors that using the sun-fixed TEC grid data, in particular, ingesting it into PRISM, offers a good possibility of meeting a 10 TECU rms ionosphere correction accuracy requirement, such as that of TOPEX/Poseidon, and should be the subject of further study. However, it is clear that the TPFO requirement of 3-4 TECU rms accuracy cannot be met by any realizable combination of the existing models and data assimilation schemes.

## Future Work

In order to meet the ionosphere calibration requirement with the methods presented in this work, a more thorough understanding of the input data is necessary. At that point, steps to improving the grid estimates for ingestion into PRISM should be made. The most obvious means for improving this method would be to take the original 642 point grid estimated at JPL and use a localized weighted interpolation to generate the sub-satellite prediction of TEC along a groundtrack, which would then be ingested into the PRISM model.

Another area of study that requires further understanding is the consistent under prediction of TEC by the PRISM base model as compared to the TOPEX/Poseidon TEC and GPS TEC measurements. The bias discovered in the TOPEX/Poseidon measurement data would account for part of the problem, and needs to be confirmed and corrected for, but will not bring all the models within the accuracy requirement. Thus, the problem still needs to be addressed more thoroughly. Among other things, a more detailed comparison

with IRI-90 may provide some insight into the consistently low TEC prediction by PRISM. Also, as the GPS network grows, the accuracy of ingesting GPS TEC derived data will undoubtedly improve. This work should be integrated with the work being carried out by SAIC on ingesting ionosonde data into the PRISM model. This is an additional data source that could contribute to the global solution.

## Acknowledgments

The authors would like to thank Captain Jeff Carson of the USAF Air Weather Service and David Anderson of the USAF Phillips Laboratory at Hanscom AFB for allowing access to the PRISM model. Rob Daniell, Bill Whartenby, and Lincoln Brown at Computational Physics, Inc., of Newton, MA, are also acknowledged for supplying a copy of the PRISM databases and source code and for assisting in the operation of PRISM. Thanks also go to Anthony Mannucci of Section 335 (Tracking Systems and Applications) at the Jet Propulsion Laboratory for supplying the biased GPS TEC data, estimates and calibrations of the receiver and satellite L1/L2 bias data, and the global TEC sun-fixed grid maps. We would further like to thank Dieter Bilitza of Hughes, STX, for providing the IRI-90 code and Lorraine Johnson of Science Applications International Corporation for insight towards understanding the PRISM weight function. At CCAR, Pete MacDoran is acknowledged for his helpful discussions throughout this work. This research was funded by NASA grant Nag-1-1491 under the direction of Steve Katzberg at NASA Langley Research Center.

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